Construction and Building Materials 187 (2018) 510–518

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Degradation of the elastic modulus of cement-based grouting material with early ages after fire

Qingtao Li [a,b], Lujie Liu [a], Zhaohui Huang [c,*], Guanglin Yuan [a]

[a] State Key Laboratory for Geomechanics & Deep Underground Engineering, School of Mechanics & Civil Engineering, China University of Mining & Technology, Xuzhou, Jiangsu 221116, China
[b] Jiangsu Collaborative Innovation Center for Building Energy Saving and Construction Technology, Xuzhou, Jiangsu 221116, China
[c] Department of Civil and Environmental Engineering, College of Engineering, Design and Physical Sciences, Brunel University, Uxbridge, Middlesex UB8 3PH, UK

HIGHLIGHTS

- Study the degradation of the residual elastic modulus of CGM after fire.
- Investigate the influence of temperatures on the elastic modulus of CGM.
- Assess the influences of the parameters on the residual elastic modulus of CGM.
- Generate a set of valuable test data for the researches and structural engineers.

ARTICLE INFO

Article history:
Received 5 March 2018
Received in revised form 26 June 2018
Accepted 28 July 2018

Keywords:
Cement-based grouting material
Curing age
Water mixing ratio
Elastic modulus
Fire

ABSTRACT

This paper presents a comprehensive experimental investigation on the degradation of the elastic modulus of cement-based grouting materials with different early curing ages after exposed to high temperature. The research focused on the influences of different temperatures, curing ages, water mixing ratio and cooling methods on the residual elastic modulus of the material. Test results indicate that the residual elastic modulus of cement-based grouting material reduces significantly after heating. The degradation of the residual elastic modulus of the material increases with increasing water mixing ratio. However, the influence of water mixing ratio is not very significant. The research indicates that the models proposed in Eurocode 2, the Chinese code and ACI-216 for normal concrete are not suitable to predict the degradation of the residual elastic modulus of cement-based grouting materials exposed to fire.

1. Introduction

In recent years, cement-based grouting material (CGM) has received considerable attentions from structural engineers and researchers due to the material has super early strength, fluidity, no shrinkage and convenient for construction [1–5]. The research conducted by Li et al. [6] indicates that temperature and water mixing ratio are main factors which affect the residual compressive strength of CGM after fire. The higher exposed temperature the lower residual compressive strength. The reduction of the residual compressive strength of the material increases with increasing water mixing ratio.

The elastic modulus of normal concrete with different curing ages at ambient temperature has been extensively studied by many researchers. Shen et al. [7] indicated that the elastic modulus of the concrete in early curing age increases with time, but the growth speed decreases against time. Zhou et al. [8] found that the growth rate of the elastic modulus of concrete before 7 days curing age is higher than the one after 7 days curing age. Li et al. [9] pointed out that the elastic modulus of concrete increases with increasing maximum aggregate size or reducing water cement ratio. The research conducted by Vilardell et al. [10] indicated that the elastic modulus of concrete increased with the increase of concrete age, and the growth rate of the specimens before the age of 28 days is higher than the one after 28 days. Shen et al. [11] found that when concrete curing age was less than 7 days, the Young's modulus of the concrete was about 1.0 to 1.3 times that of the elastic modulus of the concrete.

Shariq et al. [12] found that for normal concrete and the concrete with 40% of slag their elastic moduli were increased by 16% and 22%, respectively from the concrete with ages of 28 days to 180 days. Li et al. [13] indicated that with the increase of curing temperature (20, 35, 50, 70 °C), the elastic modulus of concrete

* Corresponding author.
E-mail address: zhaohui.huang@brunel.ac.uk (Z. Huang).

https://doi.org/10.1016/j.conbuildmat.2018.07.232
0950-0618/

decreased, also the elastic modulus of concrete decreased with increasing the diameter of fine aggregate or water cement ratio. Crouch et al. [14] found that the elastic modulus of the concrete with the porosity of 23% to 31% is higher than the concrete with other porosity. Parra et al. [15] pointed out that the elastic modulus of normal concrete is smaller than the one of self-compacting concrete and the difference increases with increasing concrete age. Wongpa et al. [16] studied the relationship between the elastic modulus and compressive strength of concrete and found that there is a linear relationship between the elastic modulus and square root of compressive strength for normal concrete.

Many researchers investigated the effects of high temperature on concrete elastic modulus [17–22]. The results indicated that the elastic modulus of concrete reduces with increasing temperature gradually. The main reasons are that high temperature results the decomposition of hydration products within concrete and the destruction of the binding key with the microstructure of concrete. The degradation of elastic modulus at high temperature depends on concrete moisture loss, high temperature creep and aggregate type. Kim et al. [20] found that the elastic modulus of concrete, after exposed to 100 °C–300 °C, reduced 10%–20% of its value at ambient temperature. After exposed to 700 °C the elastic modulus of concrete reduced to 45%–50% of its value at ambient temperature. Evandro et al. [18] found that after exposed to 600 °C, the elastic modulus of normal strength concrete reduced 51% of its value at ambient temperature and the residual elastic modulus of high strength concrete was about 41% of its original value at room temperature.

In recent years, due to some problems related to the organization and management of the construction site, there were considerable numbers of fires happened during the construction period of buildings [23,24]. When fire accident happens during the period of construction, the mechanical properties of the concrete in early age (which has not yet reached design strength of the material) will be significantly changed. Therefore, for assessing the structural safety of the building after fire it is really important to understand the mechanical properties of such early age of concrete after exposed to fire.

As mention above, considerable researches have been done on the material properties of normal concrete with early curing ages after exposed to fire. The residual compressive strength of early age cement-based grouting materials after fire has been recently investigated by the authors [6]. However, according to the authors' knowledge there are very limited researches on the residual elastic modulus of early age cement-based grouting materials after exposed to high temperatures. Because of the cement-based grouting material has high compressive strength in the early stage of construction, its elastic modulus is considerably different compared to normal concrete. Hence, it is needed to understand the elastic modulus of the early age cement-based grouting material after exposed to fire. This information is very important for structural engineers to assess the structural safety and repair ability after fire. Therefore, the main objectives of this research are:

- Conduct a series of tests to investigate the degradation of the elastic modulus of cement-based grouting materials after exposed to different temperatures.
- Study the influence of temperatures on the residual elastic modulus of cement-based grouting materials.
- Investigate the influences of different curing ages and water mixing ratios on the residual elastic modulus of cement-based grouting materials.
- Generate a set of valuable test data for the fellow researches and practical structural engineers who are interested in repairing and strengthening of reinforced concrete buildings.

2. Experimental program

2.1. Test specimens

In this research the cement-based grouting material was produced by Zhengzhou Nuweison Construction Engineering Technology Ltd. This cement-based grouting material (CGM-1) had high-strength and no shrinkage. The physical compositions and properties are presented in Tables 1 and 2, respectively. Table 3 shows the compositions of additive binding gelled material used. Based on the recommendations proposed in Chinese design code for cementitious grouting material [25], four key design curing ages of 3, 7, 14, and 28 days before heating were adopted in this study. The outcomes of previous researches [26,27] indicated that when cementitious materials were heated up to 600 °C, the compressive strength of the materials was significantly degraded. Therefore, it is reasonable to assume that the concrete structural members after exposed to such high temperature are unrepairable. Hence, in this research three level temperatures of 150 °C, 350 °C and 550 °C were used. Ref. [4] pointed out that the water mixing ratio of cement-based grouting materials is an important factor which needs to be considered. Hence, three water mixing ratios of 12%, 14% and 16% were adopted in this research. For engineering practice, water is used to extinguish a fire, so in this study the influences of water cooling and natural air cooling (natural cooling) on the residual elastic modulus were investigated. As shown in Table 4 the test specimens were divided into 72 groups. The size of the test specimens was 100 mm × 100 mm × 300 mm.

2.2. Test procedure

For this study, an electrical heating furnace GWD-05 with power of 30 kW was used to heat the specimens. The inside dimensions of the furnace are 2000 mm × 600 mm × 400 mm. The furnace has computerized temperature control system. For representing a real fire, high heating ratio was adopted. The heating rate of 10 °C /min was used for all tests [28]. In order to make sure the temperature within the specimens was uniformly distributed, the specimens were heated to the target temperature then the target temperature was kept constant for 90 min. The uniform targeted temperature within the specimens can be achieved using this heating method in the authors' previous research [6].

After the specimens were cast for 24 h, the molds of specimens were dismantled then the specimens were placed in a standard curing room with temperature of 20 ± 2 °C and more than 95% of relative humidity [29]. In order to eliminate the influence of the free water on the surface of the specimens, the specimens were cured until one day before required curing age, then the specimens were naturally dried for one day before heating. After heating the specimens were cooled down to ambient temperature under natural cooling or water cooling conditions. Then the specimens were stored in the normal lab conditions (20 °C and R.H. = 95%) until total curing time of 28 days (curing time before heating + curing time after heating) to be reached. Then the specimens were tested to generate the elastic modulus of the specimens.

For measuring the axial compressive strength and elastic modulus of the specimens, a YAW-3000 type electro-hydraulic servo

Table 1
Mix design of the cement-based grouting material (CGM-1).

Composition	High-strength cement	Quartz sand	Water reducing agent	Expanding agent
Content (wt %)	50	48.9	1	0.1